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Non-destructive grading of green Maritime pine using the vibration method

Régis Pommier · Denys Breysse · Jean-François Dumail

Abstract The purpose of this study is to estimate the modulus of elasticity of green lumber with unknown moisture content (MC) by non-destructive measurement. This paper reports the results and statistical analysis of a large number of experiments. They indicate that the dynamic modulus of elasticity (DMOE) can be determined without knowing the MC. Mechanical grading with DMOE determined in this way is reliable and efficient with a correlation coefficient of 0.44, compared with a coefficient of 0.45 between MOR and DMOE of dry specimens. Thus the possibility of strength grading of Maritime pine (*Pinus pinaster*) at an early step in the industrial process is demonstrated with success.

Sortierung von frischem Küstenkiefernholz mittels zerstörungsfreier Schwingungsmessung

Zusammenfassung Ziel dieser Studie war es, den Elastizitätsmodul von frischem Schnittholz mit unbekannter Holzfeuchte (MC) mittels zerstörungsfreier Messung zu bestimmen. In diesem Artikel werden die Ergebnisse sowie die statische Analyse einer großen Anzahl von Versuchen beschrieben. Sie zeigen, dass der dynamische Elastizitätsmodul (DMOE) bestimmt werden kann, auch wenn die Holzfeuchte nicht bekannt ist. Eine mechanische Sortierung mit dem so bestimmten DMOE erwies sich mit einem Korrelationskoeffizienten von 0,44 als zuverlässig und effizient im Vergleich zu einem Korrelationskoeffizienten von 0,45 zwischen Biegefestigkeit (MOR) und DMOE von trockenen Prüfkörpern. Damit wurde gezeigt, dass die Festigkeitssortierung von Küstenkiefernholz (*Pinus pinaster*) bereits in einer frühen Phase des Herstellprozesses möglich ist.

1 Introduction

Maritime pine (*Pinus pinaster*) from the south-west of France represents 8 million m^3 of yearly sawn production. The quality of the clear wood is excellent for the competitive furniture industry. Product quality in the furniture industry is more and more required with respect to the competitiveness of the product market. However, this resource is clearly not homogeneous. The presence of knots and curvy trunks provide low quality timber for structural uses. The lumber is currently graded in sawmills. Although the standards state that timber grading can be carried out visually this technique prevents any high speed process. Using non-destructive evaluation techniques to predict the material properties of wood as quickly as possible in the manufacturing process is a matter of considerable importance for the timber industry (Köhler 2007; Wessels et al. 2011). Machine grading is used in sawmills on dry timber (after drying to service moisture content). The aim is to highlight the feasibility of grading in a green state with a high speed machine.

The quality of sawn timber is defined by high processing accuracy, the quality of the raw material, good design and the consistence of these aspects over time (Cariou 1987). Concerning the timber frame market, the quality requirements focus on mechanical performance and guarantee a set of minimum design properties prescribed in EN 1995 (2004). Assessment of the mechanical properties of timber

R. Pommier (✉) · D. Breysse · J.-F. Dumail
Département Génie Civil Environnemental (GCE), UMR 5295, I2M, Université Bordeaux1/CNRS/INRA, 351 cours de la Libération, 33400 Talence, France
e-mail: regis.pommier@u-bordeaux1.fr

J.-F. Dumail
EURL Xylomeca, Moulin Neuf, France

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by non-destructive methods is achieved by vibration methods, stress graders, optical scanning methods, etc. The literature widely documents the possibility of predicting static MOE at MC = 12 % from dynamic modulus of elasticity (DMOE) at the same moisture content (MC). DMOE also appears to be a potential predictor for MOR (Larsson and Ohlsson 1998).

Vibration methods have been successfully used to estimate the density and mechanical properties of wood and wood-based composites in scientific research and in the forest products industry for several decades (Moslemi 1967; Renaudin and Breysse 1999; Ilic 2003). In comparison to conventional static bending tests, the vibration methods are non-destructive, rapid, convenient to use and inexpensive. They have therefore been used for grading structural lumber and evaluating the quality of laminated materials (Green et al. 2004).

Ross and Pellerin (1991; 1994) and Ross et al. (1998) examined the relationship between longitudinal stress wave velocity and static MOE for Douglas fir lumber. They observed strong linear relationships ($r = 0.95$). Ross et al. (1991) used transverse vibration techniques to estimate the quality of spruce–pine–fir lumber and observed a useful relationship between the DMOE and MOE ($r = 0.99$). For timber frames in structural dimensions, Larsson and Ohlsson (1998) presented some interesting results on 530 samples (38×184 mm^2) of *Picea abies* (Table 1).

These correlations were confirmed for Maritime pine (Dumail and Morlier 2004). It was concluded that the method may be successfully used for mechanical grading of Maritime pine in structural size ($50 \times 150 \times 4,000$ mm^2).

A study by Dumail and Morlier demonstrated that for a given sawmill production the vibration technique generated fewer rejects (percentage of wood with a load-bearing quality lower than C18 according to EN 1995) than the visual grading technique according to EN 14081 (2005) (8 % compared to 47 %).

Recently Yin et al. (2005) have used transverse dynamic modulus of elasticity with transverse vibration on Canadian conifers. The same types of results were obtained by Jiang et al. (2008) with natural Mongolian Scots pine and Chinese fir. They showed that this dynamic modulus of elasticity has a significant linear correlation with static MOE. This method also produces good results using engineering wood like glulam.

Wang et al. (2008) show that the transverse vibration test is the best non-destructive method to evaluate sawn timber and structural glulam. Finally Zhang et al. (2010) tested dynamic modulus of elasticity of larch dimensional lumber with ultrasonic waves, and measured static MOE with a bending test. They also concluded that there is a good linear relationship between MOE and dynamic modulus of elasticity.

Table 1 Experimental correlation between NDT DMOE and static MOR or MOE

Tab. 1 Experimentelle Korrelation zwischen dem zerstörungsfrei bestimmten DMOE und statischer Biegefestigkeit (MOR) bzw. statischem E-Modul (MOE)

References	Material	N.	R^2
Correlation MOR vs. MOE/DMOE			
Larsson and Ohlsson (1998)	Spruce (38×89 mm^2)	122	0.47/0.39
	Spruce (38×140 mm^2)	127	0.61/0.61
	Spruce (38×184 mm^2)	274	0.56/0.58
Correlation MOE vs. DMOE			
Wang et al. (2008)	Japanese cedar	198	0.77
	Taiwania	302	0.79
	Douglas fir	163	0.97
	Southern pine	123	0.94
Yang et al. (2008)	Douglas fir	657	0.83
	Japanese cedar	550	0.80
Yin et al. (2005)	Pine spruce	62	0.85
	Fir spruce	62	0.88
Ilic (2001)	Eucalyptus	51	0.98
Yang and Luo (2011)	Poplar	22	0.52
Casagrande (1998)	Maritime pine	30	0.7

N. number of tests

Table 1 summarizes the outcomes of these studies on the correlations received for this project, showing the specific correlations examined, material tested, specimen sizes, number of specimens, R^2 coefficient.

To the best of the authors' knowledge, studies have not yet addressed the use of the vibration method to assess the structural grade of green timber at the beginning of the sawmill process (EN 14081-4: 2005), when sections are determined for future processing (Pommier and Elbez 2006). Recent studies (Unterwieser and Schickhofer 2011) have analyzed how the velocity of sonic waves and their natural frequency are changed above the saturation point.

The overall goal of the present study is thus to investigate the possibility of using the dynamic modulus of elasticity DMOE, or dynamic method, for the assessment of structural grades in sawn timber at an earlier stage of the sawing process, when the moisture content is above fibre saturation.

2 Materials and methods

2.1 Experimental program

The material is Maritime pine (*Pinus pinaster*) harvested from different stands in the south-west of France. The

average density of this type of timber is d = 0.45 g/cm^3, and the average modulus of elasticity MOE = 11 GPa, at 12 % moisture content (Guitard 1987).

The specimens for this study were taken from common industrial sawmill processes before drying.

The raw material was assigned to three sets in which specimens of different geometries were used to examine various aspects of the correlations between the condition and other properties of interest.

Set 1 was comprised of 110 samples of small clear wood specimens (section 20 × 20 mm^2, length 360 mm). The material came from a single sawmill processing wood from all over the south-west of France. These specimens were used to determine the changes in MC and DMOE of clear wood at green condition, at 48 % MC (above FSP) and at 18 % MC (considered commercially dried). The first measurements were performed immediately after sawing. Analysis of Set 1 enables to determine how Dynamic MOE (DMOE) varies at different moisture contents between its green condition and dry-air conditions. The two other sets concern timber and are helpful in analyzing:

- how static and dynamic moduli vary with the moisture content,
- how static and dynamic moduli are correlated,
- how strength (MOR) can be predicted from stiffness measurements, either static (MOE) or dynamic (DMOE).

Set 2 was comprised of 198 boards (cross-section 22 × 100 mm^2, length 1.20 m). This set includes both clear wood and wood with whirls of knots, representing proportionally wood from different parts of the trees (lower trunk, middle trunk, crown section). This reflects the complex natural variation in Maritime pine properties at a tree scale. These specimens were used to determine the changes in MC, DMOE, MOE and MOR at green condition, at 48, 18 and 12 % MC. The first measurements were performed immediately after cutting the samples from

green material. At each successive stage specimens were used for destructive bending tests.

198 beams were first tested to determine DMOE at MC = 130 %. Each beam is stored in a climatic chamber (RH = 65 %, T = 20 °C), once equilibrium was reached.

Set 3 was comprised of 225 planks (27 × 80 mm, 2 m-long) collected from four different sawmills to represent the variability of the Maritime pine species on a regional scale. They were visually pre-graded to consider only C24 material. These samples correspond to four geographical areas of the south-west region of France (Aquitaine), influenced by the same climate but different soil conditions. The respective subsets are respectively: Dordogne (18 specimens), Wet Landes (40 specimens), Dry Landes (73 specimens) and Sand Dunes (94 specimens). They were first dynamically tested in a green state. These specimens were used to determine the variability in the correlations between properties measured at green conditions (DMOE) and air-dry (12 %) conditions (DMOE, MOE and MOR). Table 2 presents the information determined for each of the three sets. The two larger values of MC respectively correspond to green condition (considered about 130 %) and to a value (48 %) above fibre saturation. It must be specified that due to the heterogeneity of the material and the experimental process itself (all specimens taken out of the climatic chamber at the same time), the exact target value of moisture content had not been reached by all specimens. For instance, the MC = 48 % target value for Set 1 corresponds in fact to an average value of 46.6 %, but with a very large coefficient of variation of 45 %.

It is necessary to note that for Set 1 and Set 3 all specimens (wood sample in Set 1 and timber in Set 3) were marked individually, which makes it possible to monitor all through the series of measurements and identify correlations on an individual basis. For Set 2, the specimens were unmarked and it was only possible to work on the statistics for the entire populations.

Table 2 Synthesis of available information
Tab. 2 Zusammenfassung der verfügbaren Versuchsergebnisse

	Set 1	Set 2	Set 3
Number of specimens	N = 110 (102)	N = 198	N = 225
Cross section (mm^2)	20 × 20	22 × 100	27 × 80
Material origin	Small scale specimens, various areas	Beams, single tree	Beams, various areas
MC = 130 %	DMOE	DMOE	DMOE
MC = 48 %	DMOE	DMOE, MOE–MOR (62)	
MC = 28 %		DMOE	
MC = 18 %	DMOE		
MC = 12 %		MOE–MOR (28)	DMOE, MOE, MOR

In parentheses: final number for analysis

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2.2 Drying procedures

The first measurements were performed on green material immediately after cutting of the specimens. After that, the specimens of Set 1 and 2 were progressively dried in a climate chamber at 20 °C and 65 % relative humidity (RH). The MC was monitored by the mass measurement of some samples.

Further tests were performed according to the schedule in Table 1 when the MC reached values of 48, 28, 18, and 12 %.

For Set 2, after the first measuring, DMOE was measured at about MC = 48 %. At this stage, 70 specimens were tested in 4-point bending flatwise; MOE and MOR being determined according to EN 408 standard. Due to experimental problems, only 62 (MOE, MOR) pairs could be considered for analysis. The remaining beams were further dried and a third DMOE measurement was taken when the remaining specimens reached MC = 28 %. 28 specimens were finally dried to MC = 12 %.

For Set 3, after the first measurement of DMOE with green timber, samples were industrially dried at 60 °C for 7 days to a moisture content of 12 %.

2.3 Determination of material properties

- volumic mass

Volumic mass and MC are obtained by mass measurement according to EN 13183-1 (2002).

- Static MOE and MOR

Static MOE and MOR are determined using the 4-point bending test flatwise as defined by EN 408 (1995) for Set 2 and Set 3. An additional series of tests was performed at MC = 48 % for Set 2 in order to compare the variation of MOE and MOR with water content.

- Dynamic MOE

The dynamic modulus of elasticity was determined via vibration method focusing on EN 14081. The principle of the vibration method is the measurement at one end of a free support beam of the first natural frequency after an impact at the other end. The dynamic modulus of elasticity (DMOE) in the longitudinal direction may be deduced from this natural frequency, weight and dimensions.

The DMOE can be quantified following the equation by Timoshenko et al. (1974) using vibration of a beam (Murphy 2011):

$$DMOE = \frac{f^2 S^4 \, w \, 12}{\pi^2/4 \, gL \, bh^3} \tag{1}$$

where g is gravitational (acceleration) constant; S is the support span ($<$L); L is the length of the beam; f is the frequency of vibration; w is the weight of specimen; b and h are the width and the height of the cross section.

Set 1 was measured under laboratory conditions, bending vibrations being detected by an accelerometer at the other end of the impact. Vibration modes were monitored using a Pico Technology package (ADC216; 16 bits) and software especially developed in the laboratory that takes into account different free vibrations transformed into different frequencies by Fourier transformations.

Set 2 and 3 were measured following the same principle. The grader has an automated device unit and dimensions are assessed using a laser-optic device.

3 Results

As explained in Sect. 2.1 and Table 2, the three Sets were analyzed in order to study the strength correlation of static and dynamic modulus at various moisture contents, how the various measurements can be correlated and how strength (MOR) can be predicted from non-destructive measurements. Data post-processing of Set 1 reveals that a series of 8 samples has inconsistent DMOE values. Therefore, 102 values were kept for analysis.

In a first stage, the authors focused on statistical distributions and data consistency as reflected by the cumulative distributions. In the second step statistical correlations of each result were analyzed.

3.1 Statistical properties and cumulative distributions: Influence of MC

The three Sets provide information about average material properties and variability at various scales. Tables 3 and 4 respectively synthesize the statistical information obtained for MOE and DMOE from the different Sets and moisture conditions (MC): the means show coefficients of variation (CoV) and the medians with their characteristic values obtained by cumulative distribution with 95 % confidence level. For example, the Table shows how the MOE and MOR vary between 48 and 12 %. Figure 1 shows how the cumulative distribution of DMOE varies with MC.

It has been recognized since a long time that MOE and MOR standard values obtained during static tests under standard loading conditions are highly dependent on the moisture content of timber. Many previous studies have analyzed this dependency (Wood Handbook 2010; Tsoumis 1991). According to the Wood Handbook, a decrease by about 40 % for MOE and 30 % for MOR can be anticipated between 10 % MC and green conditions. Results in Table 3 show a decrease by about 40 % for both average values of MOE and MOR between 12 % MC and 48 % MC. This decrease is even larger for characteristic

values (last column of Table 3: MOE and MOR at 0.05 percentile).

In Table 4 the results of Dynamic modulus of elasticity for Sets 1, 2 and 3 are represented.

Regarding dynamic modulus, the results are very different. It can be seen from Table 4 and Fig. 1 that the statistical properties (mean, median and characteristic values) and statistical distribution remain almost constant above and below fibre saturation point. A slight decrease of the mean DMOE value was detected when MC decreases for Set 1 and Set 2, but Set 3 reveals a reverse effect. The characteristic DMOE value has also a very limited sensitivity to MC. This is a very interesting point for the assessment of structural grades of green timber.

The variability is larger for Set 2 than for Set 1, since Set 2 contains material of a very variable quality (clear wood but also wood with whirls of knots). Even if it is a batch comprising wood from various geographical origins, Set 3 is more homogeneous since it corresponds to visual grade C24 already selected at the mills. Regarding Set 1, a further look at the curves reveals a bimodal distribution

with a subset that can be distinguished in the lower values (Fig. 1). Composed of small samples of clear wood, the Set can contain a large part of juvenile wood specimens with low density. For example, the eight samples having a modulus lower than 5000 MPa have been found to also have the lowest volumic mass values, which together indicate juvenile wood.

The high consistency of DMOE measurements for Set 3 is confirmed by Fig. 2, where DMOE measured at green and dry (12 %) state for each population are compared for the four geographical subsets. The regression analysis for each population (sub-region) separately yielded slopes between 0.87 and 0.90, with a correlation always above $R^2 = 0.7$. The regression tests performed on this subset are not statistically different at the 0.95 confidence level (and therefore may be pooled together for further analysis). For the pooled data the coefficient of determination was at 0.75.

3.2 Statistical correlations between material properties

3.2.1 Correlations between volumic mass and mechanical properties

volumic mass is often used as a (partial) predictor for timber stiffness or strength, since these properties appear to be positively correlated (Dinwoodie 2000).

Experimental results should be synthesized as:

- volumic mass = 508 kg/m³ at 18 % MC for Set 1,
- volumic mass = 594 kg/m³ at 12 % MC and volumic mass = 810 kg/m³ at 130 % MC, for Set 3.

The variability of the volumic mass is about twice as small than that of modulus and it is about 9–12 % at a dry state. The variability is larger for greenwood (MC = 130 %), mainly because the exact value of MC may also vary from one plank to another.

Table 3 Statistical properties of MOE and MOR for Set 2 and two MC values
Tab. 3 Werte des Elastizitätsmoduls und der Biegefestigkeit des Kollektivs 2 bei zwei Holzfeuchten

Set	MC (%)	N.	MOE_{mean}	CoV (%)	MOE_{median}	$MOE_{0.05}$
2	48	59	6,640	48	5,930	2,190
	12	27	11,260	24	10,840	7990

	MC (%)	N.	MOR_{mean}	CoV (%)	MOR_{median}	$MOR_{0.05}$
	48	59	35.6	38	34.8	15.7
	12	27	60.5	25	57.6	39.2

MOE and MOR in MPa, characteristic value corresponds to a 5 % lower fractile

Table 4 Statistical properties of DMOE for the three Sets and all MC values
Tab. 4 Werte des dynamischen Elastizitätsmoduls (DMOE) der drei Kollektive bei allen Holzfeuchten

Set	Material	N.	MC (%)	$DMOE_{mean}$	CoV (%)	$DMOE_{median}$	$DMOE_{0.05}$
1	SCS	94	130	8,880	22	9,270	4,730
		94	48	8,920	23	9,380	4,700
		94	18	8,410	21	8,530	4,610
2	Timber	198	130	8,150	34	7,620	4,530
		198	48	7,910	28	7,900	4,920
		198	28	7,940	30	7,940	4,580
3	Timber	225	130	11,240	19	11,330	8,100
		225	12	12,700	19	12,750	8,790

DMOE in MPa, characteristic value corresponds to a 5 % lower fractile

SCS small clear stress-graded specimen

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The linear regression of volumic mass with the dry DMOE for Set 1 (small specimens, here at MC = 18 %) appears to be good with $R^2 = 0.68$ (Fig. 3), but it is much poorer for Set 3 (timber, here at MC = 12 %) both for MOE (Fig. 3b) and DMOE (Fig. 3c). When timber is considered, it is known that modulus depends on many factors other than volumic mass, among which are large in-homogeneities, such as knots and the grain angle, thus the correlation between volumic mass and modulus is weaker. The determination coefficient here is $R^2 = 0.136$ for MOE and 0.236 for DMOE. These correlations are too poor to be of practical use to predict the stiffness properties from volumic mass measurements.

Even if it is of low statistical significance, the underlying relationship between volumic mass and DMOE on timber has a real consistency. Some interesting information
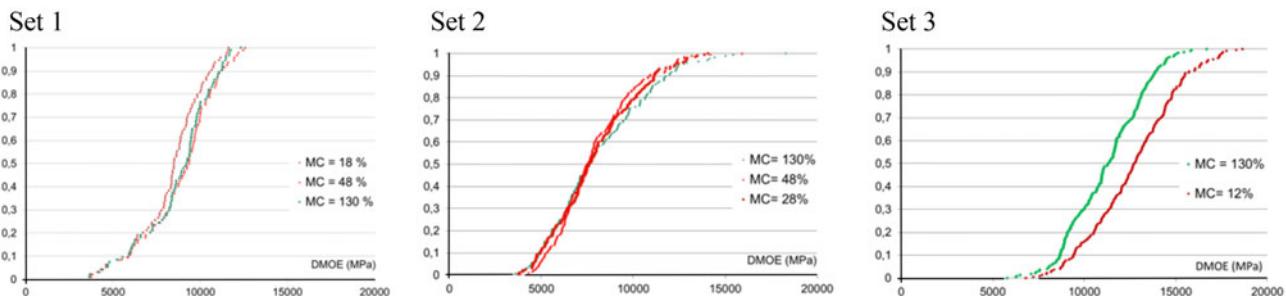
Fig. 1 Cumulative distribution of DMOE for three MC values for Set 1, Set 2 and Set 3
Abb. 1 Häufigkeitsverteilung des dynamischen Elastizitätsmoduls der drei Kollektive 1, 2 und 3 bei drei Holzfeuchten

Fig. 2 DMOE measurements in dry and green conditions, Set 3
Abb. 2 Dynamischer E-Modul des Kollektivs 3, bestimmt in trockenem und grünem Zustand
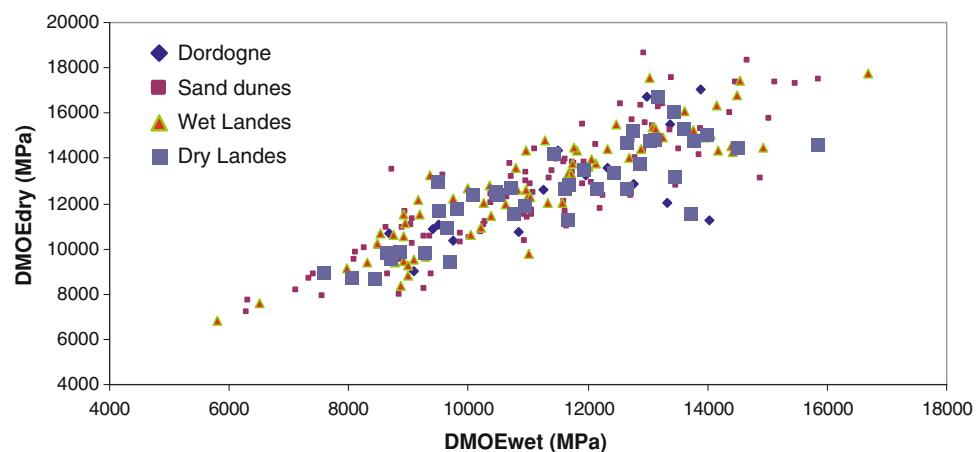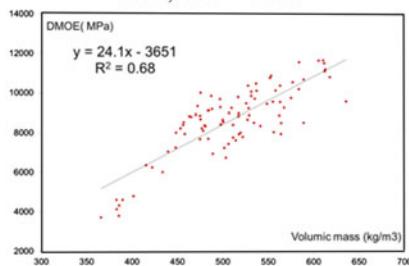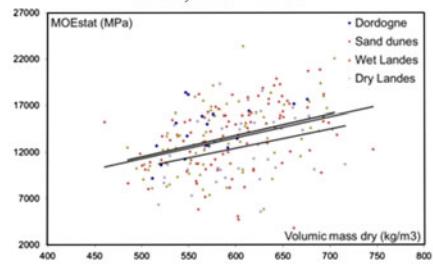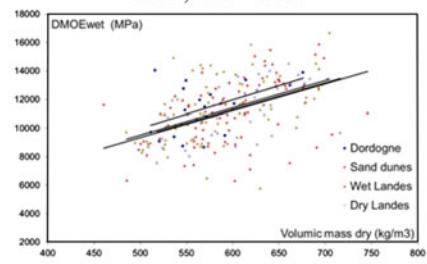

Fig. 3 Correlation between: **a** volumic mass and dynamic modulus (Set 1, MC = 18 %), **b** volumic mass and static modulus MOE (Set 3, MC = 12 %), **c** volumic mass and dynamic modulus DMOE (Set 3, MC = 12 %)
Abb. 3 Korrelation zwischen **a** Dichte und dynamischem E-Modul (Kollektiv 1, MC = 18 %), **b** Dichte und statischem E-Modul (Kollektiv 3, MC = 12 %), **c** Dichte und dynamischem E-Modul (Kollektiv 3, MC = 12 %)

Table 5 Statistical properties for volumic mass (VM in kg/m^3) and dynamic modulus of elasticity (DMOE in MPa) for the four subsets of Set 3

Tab. 5 Werte der Dichte (VM in kg/m^3) und des dynamischen E-Moduls (in MPa) der vier Herkünfte des Kollektivs 3

	Green Timber		MC = 12 %	
	Mean	CoV (%)	Mean	CoV (%)
VM$_{Dordogne}$	714	14.7	571	8.0
VM$_{Wet\ Landes}$	801	16.1	607	8.7
VM$_{Dry\ Landes}$	857	14.7	586	9.6
VM$_{Sand\ Dunes}$	795	13.7	598	9.3
VM$_{all}$	810	15.3	594	9.3
DMOE$_{Dordogne}$	11,400	16.0	12,470	18.7
DMOE$_{Wet\ Landes}$	11,410	17.7	12,620	16.7
DMOE$_{Dry\ Landes}$	11,170	19.5	12,740	19.2
DMOE$_{Sand\ Dunes}$	11,190	19.1	12,760	20.8
DMOE$_{all}$	11,240	18.7	12,700	19.4

can be obtained by looking further into the four geographical subsets. Table 5 summarizes information about volumic mass and DMOE in dry (MC = 12 %) and green conditions.

Data confirm first the lower variability (CoV) of volumic mass in dry condition, and second the low sensitivity of DMOE values to MC variations. The four subsets have very comparable mechanical properties, as can be seen by comparing mean values of DMOE for the four subsets either at MC = 130 % or at MC = 12 %. This is logical since, despite their different geographical origins, all these timber specimens have been graded to C24 according to EN 1995. While the volumic mass at a uniform moisture content, that is for example at MC = 12 %, air dry or even dry condition, is a good predictor of mechanical properties, it cannot be effectively used in the green condition because of the substantial variability of the MC in the green wood. In theory the green volumic mass values could be adjusted to the actual MC of each piece. The exact in-line measurement of MC above FSP is difficult and therefore not performed in sawmills.

3.2.2 Correlations with strength modulus MOR

The aim of timber grading is a reliable assessment of strength by the measurement of non-destructive properties. It is thus of key importance to check the validity of correlation between MOR and such parameters. Correlation relationships can be established between MOR (which remains the strength reference according to Standards) and a variety of NDT properties. Such links are summarized in Fig. 4.
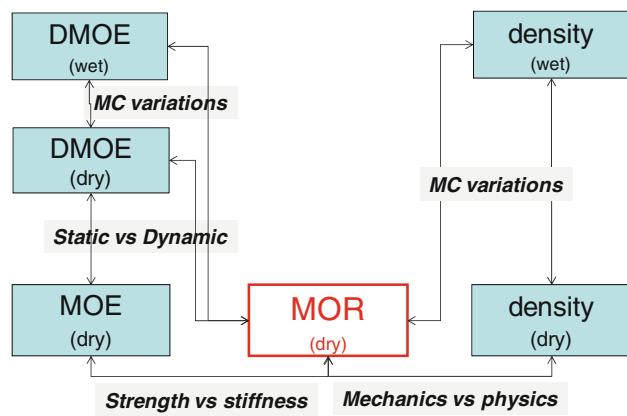
Fig. 4 Mapping of relationships between strength and non-destructive properties

Abb. 4 Beziehung zwischen der Biegefestigkeit und zerstörungsfrei bestimmten Eigenschaften

Five elements must be accounted for when studying these relationships, since they may affect the quality of the correlation, therefore impacting the efficiency of assessment:

– the measurement of a physical property (like volumic mass) only provides partial information on mechanical properties such as strength,

– any non-destructive mechanical measurement only provides partial information on strength, since the failure process may activate processes other than those involved in the elastic domain (in which most usual non-destructive tests remain),

– regarding stiffness measurements, static and dynamic measurements correspond to different means of solicitation. The latter remains elastic when the former may activate non-linear effects like those due to visco-elastic behavior,

– any measurement performed at a different moisture content than the reference condition ("dry" at MC = 12 %) may induce biases,

– in addition, the same figure can be drawn both for timber and clear wood. The fact is that the validity of correlations established on clear wood may be very debatable if applied to timber.

The target here is to highlight the advantage of using DMOE measurements on timber while in green condition in order to assess MOR (and thus to enable timber grading). In the following these various elements will be addressed. The quality and validity of correlations built between these parameters on Set 1 (clear wood) and Set 3 (timber) will be discussed.

The third Set of samples was tested to correlate grading of Maritime pine by non-destructive testing on green wood.
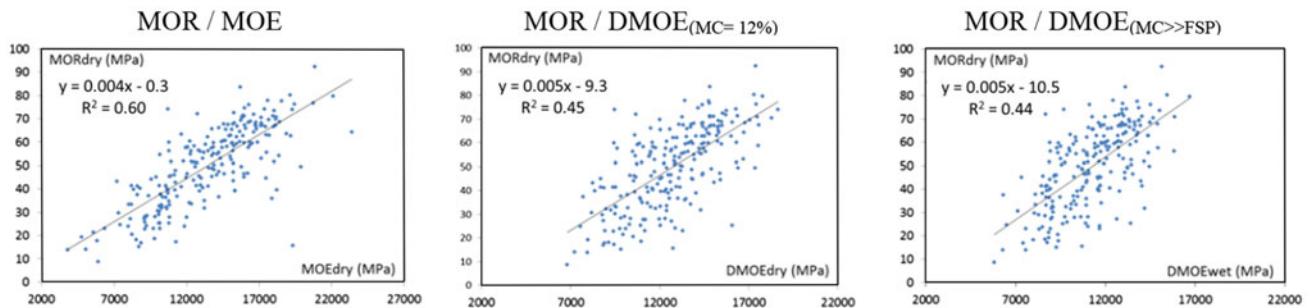
Fig. 5 Relationship between MOR (standard tests) and different MOE for Set 3
Abb. 5 Zusammenhang zwischen der Biegefestigkeit (Standardprüfungen) und verschiedenen E-Moduli des Kollektivs 3

Results of DMOE on green wood, DMOE, MOE and MOR in dry condition (MC = 12 %) are presented in Fig. 5. Note that the MOR for Set 3 is always measured in dry condition.

Correlation between MOR and MOE in dry condition is well known for Maritime pine (Dumail and Morlier 2004). It is determined with a determination coefficient $R^2 = 0.60$ (Fig. 5). The determination coefficient is only slightly decreased for $DMOE_{dry}$ ($R^2 = 0.45$) and $DMOE_{green}$ ($R^2 = 0.44$).

In practice, this correlation can be used by establishing the empirical equation of the MOR-X parameter in a calibration stage. Then this relation can be used for predicting the MOR value on any new specimen by the single X measurement of the predictor value, where X may be MOE, $DMOE_{dry}$ or $DMOE_{wet}$. The efficiency of such a strategy can be quantified through the root mean square error (RMSE) on MOR. The empirical regression model and the RMSE (Root Means Squared Error) could be summed up:

– For MOE: MOR = 0.00373 MOE −0.26, $R^2 = 0.60$, RMSE = 13.9 MPa,
– For $DMOE_{dry}$: MOR = 0.00464 $DMOE_{dry}$ −9.27, $R^2 = 0.45$, RMSE = 12.5 MPa,
– For $DMOE_{wet}$: MOR = 0.00536 $DMOE_{wet}$ −10.52, $R^2 = 0.44$, RMSE = 12.7 MPa,

It is interesting to note that the mean RMSE is even lower for the two models with DMOE, because of a smaller number of outliers. Figure 6 shows correlation coefficients for all correlations that have been identified for Set 3.

The DMOE measurement on green planks has potential for economic advantages, since it may be easily included in the sawing process and carried out on all planks. Its efficiency for estimating the MOR value of the dry plank is almost the same as that of the static MOE in dry conditions. This is a key argument in favor of this way of grading timber.
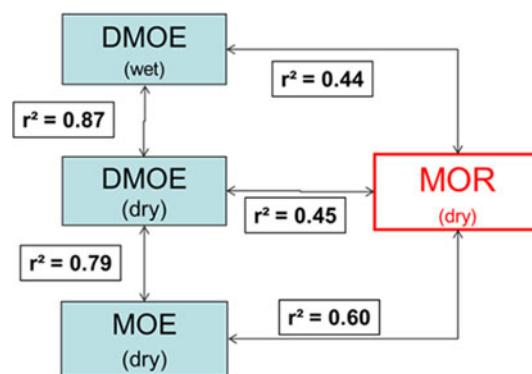

Fig. 6 Determination coefficients on timber between MOR and (non-destructive) stiffness parameters
**Abb. 6** Bestimmtheitsmaße für die Verhältnisse zwischen Biegefestigkeit (MOR) und (zerstörungsfrei bestimmten) Steifigkeitsparametern

4 Discussion

The results presented above show that DMOE in green condition (without the necessity to measure the MC value) or DMOE at an air dry MC in the 12 to 18 % range, or after drying (MC = 12 %) may be used to predict the MOR of timber at MC = 12 %. This statement is justified by the elements discussed in the following.

4.1 Quasi invariability of DMOE

From the experiment performed on Set 1 and Set 3 (specimens with different dimensions and qualities) it can be concluded that for Maritime pine DMOE values remain invariable versus MC. The result of DMOE was similar both above and below FSP. Figure 7 shows the ratio between the dynamic modulus of elasticity measured at various MC and that measured at green conditions ($DMOE_{MC}/DMOE_{green\ wood}$) for their moisture contents: 12, 18, 48 %. Variations (increase) are <10 % for dried wood, compared to more than 40 % for dry static MOE.

Fig. 7 DMOE/DMOE$_{green\ wood}$ for Sets 1 and 3
Abb. 7 DMOE/DMOE$_{green\ wood}$ bei den Kollektiven 1 und 3
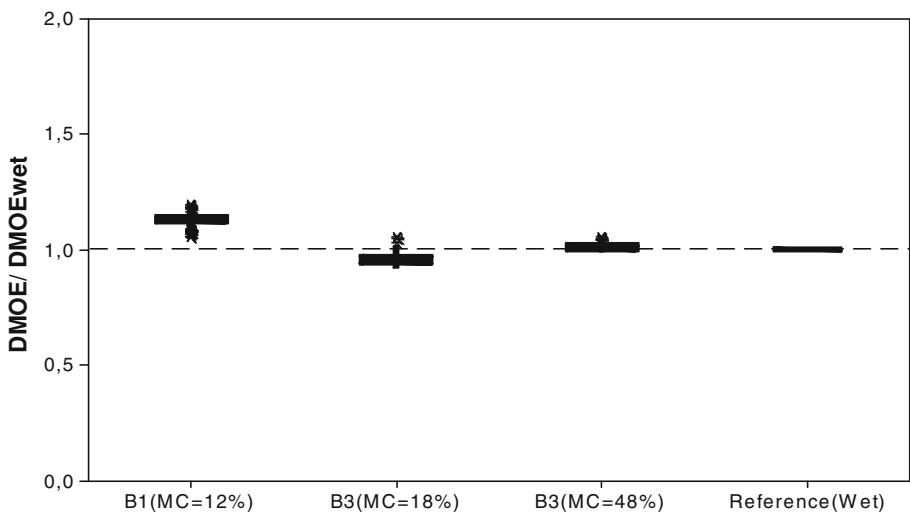
It is only under standard conditions (Temperature = 20 °C, MC = 12 %) that MOE values were statistically similar whether obtained using the static or vibration methods. The boundary between what is by convention considered "static", "dynamic" or "long term" loading condition is fluid whose rheology is affected by temperature or MC.

Two explanations for the quasi invariability of DMOE versus MC should be hypothesized:

- Using Eq. 1, it is possible to determine dynamic modulus of elasticity. In this equation, the two parameters namely volumic mass and eigenfrequency, may have a compensating effect, both increasing with moisture content.
- Another explanation may be due to the viscoelastic behaviour of wood [possibly modelled by the rheological model of Kelvin-Voigt (Navi and Sandberg 2012)]. The adiabatic instantaneous solicitation in dynamic bending can be compared with the static bending test which is influenced by the viscoelastic response when moisture content increases. Subsequently, during a static bending test, the response behaviour might be time dependent further affected by MC and/or temperature. In dynamic testing this time dependent response becomes specifically negligible.

4.2 Regression model between DMOE and MOR

Figure 5 provides the regressions between MOR and MOE values (dynamic and static). The coefficient of correlation between each measure for Sets 1 and 3 is represented by a linear regression model of the form $Y = aX + b$.

The grading function, MOR = 0.00536 DMOE$_{wet}$, can be used to estimate the MOR of any sample from DMOE. A satisfying correlation between DMOE and MOR can be explained by:

- The strong correlation between the green and dry DMOE $R^2 = 0.87$. The correlation between the DMOE green and DMOE dry with MOR are similar with R^2 about 0.45.
- The strength of the correlation between MOR and static MOE may be explained by the fact that both are focussed on the central 1/3 of the specimen length, while the dynamic properties are affected by the entire specimen volume.

4.3 Grading of softwood

Grading of softwood is possible by non-destructive testing at undetermined moisture content. The machine controlled system given in EN14081 incorporates uncertainties in the grading model only implicitly, i.e. by sampling of different subsamples of different origins and by comparing assigned grades with optimum grades. The performance of the output control system is observed to be capable of detecting aberrations in the quality of the material supply. The method is still based on sample statistics and therefore only capable of detecting shifts in quality of the timber supply. The correlation of DMOE and MOR at MC = 12 % is still used on an industrial scale. The correlation between DMOE at undetermined MC and MOR can be used in a similar way. The relationship, estimating the modulus of rupture from DMOE in green state is given. Implemented in a machine, the regression analysis to indicate the relationship between MOR and the indicating property (measurement carried out in green state) should have different boundary values from measurement in a dry state in order to ensure the same C24, C32, C40, etc. grading (EC5). The fact that the correlation is established instead of DMOE$_{dry}$ and DMOE at unmeasured MC introduces an additional influencing parameter (MC) and results in a very small decrease of R^2.

Concerning Maritime pine, machines are traditionally used for grading at C24. This corresponds to the lowest properties of the sets studied in this paper according to the characteristic values in Fig. 1. The characteristic DMOE are independent of MC. C24 grading DMOE could be used at undetermined moisture content without modifying the relationship still used by the industrial grading machines.

To the best of the authors' knowledge, these physical observations are reported for the first time and they could improve the mechanical grading of wood since the correlation between DMOE values and MOR is of the same quality for standard green wood (MC = 12 %) and for undetermined moisture content (Fig. 5).

5 Conclusion

More than 400 samples were used to characterize Dynamic Modulus of Elasticity (MOE) at various MC conditions. It was demonstrated that the DMOE is not sensitive to MC level in a wide MC range (green to 18 %). The strength of the correlation between $DMOE_{green}$–MOR is only slightly weaker than that of static MOE_{dry}–MOE (0.438 compared to 0.598).

The applicability of these findings to the strength grading of Maritime pine "Pinus pinaster" at an early stage in sawmill machines is being considered in a pilot scheme and developed for other species. In any case, automatic grading will ensure the reliability of the mechanical grading based on green DMOE, and thus ensure the EC marking for the process.

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